A Multi-ion Model of the Heliosphere with Secondary Charge Exchange

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The heliosphere

- Solar wind (SW)– (mostly) hydrogen plasma streaming radially outward from Sun, **~400-800** km/s (supersonic), **~50 000** K

- Local interstellar medium (LISM) – flows uniformly, **~26** km/s (subsonic?), **~8 000** K

- SW and LISM separated by contact discontinuity, the heliopause (HP)

- SW becomes subsonic at termination shock (TS)

Regions of the heliosphere
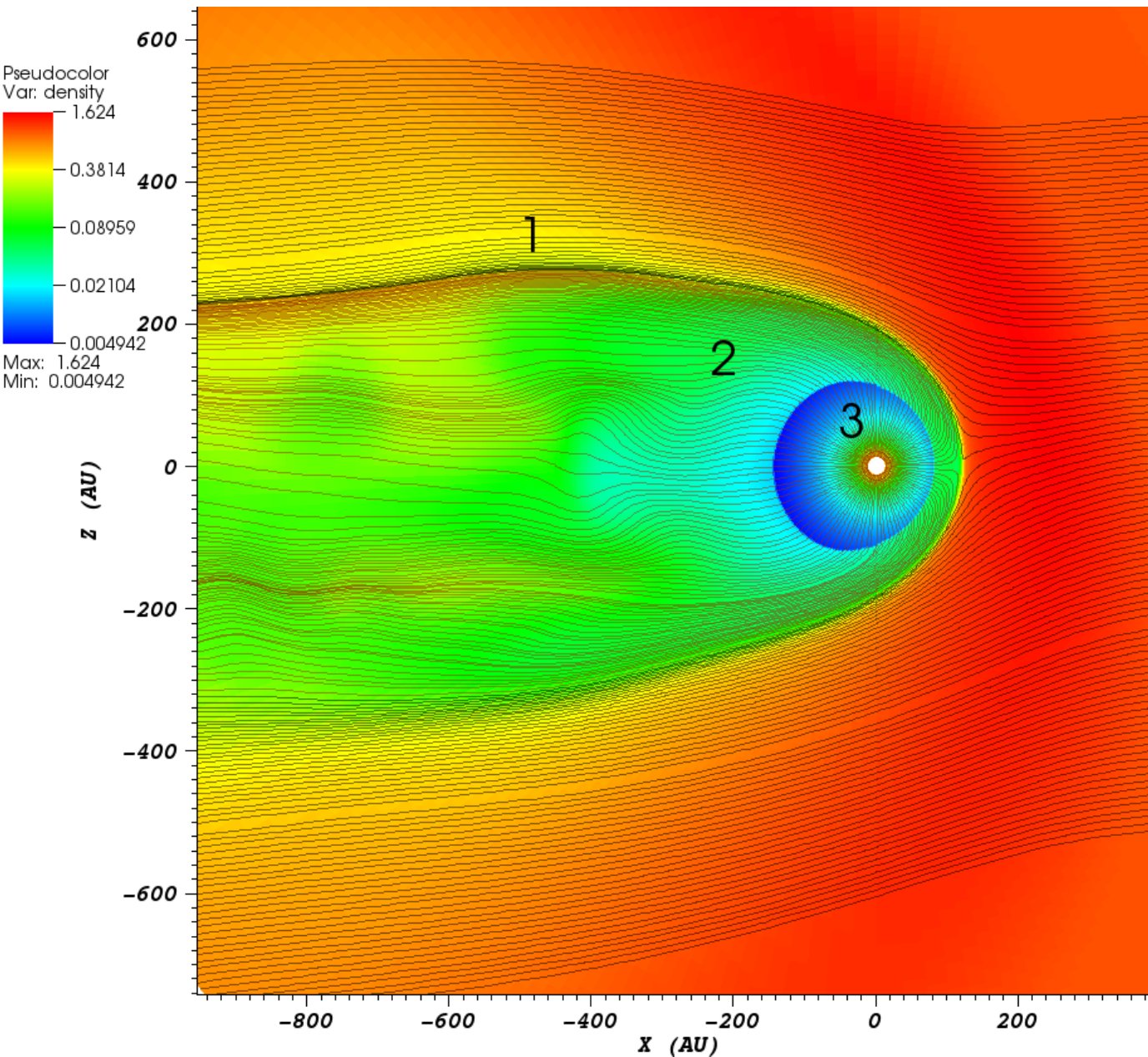
- LISM plasma flows from the right, around the HP
- Neutral atoms not affected
- SW plasma blown to the left along with LISM
- LISM slows ahead of HP
- Abrupt jump in density at TS

Charge exchange and pickup ions (PUIs)

- Fast SW ion and slow LISM neutral atom exchange electron, yielding fast neutral atom and slow ion (in observer frame)

- New ions gyrate around magnetic field in ring-beam distribution with radius close to the SW streaming velocity

- New ion distribution rapidly isotropized by MHD waves, "picked up" by motional electric field $\vec{E} = -\vec{U} \times \vec{B}$ until co-moving with parent ions (the "core" SW)

- PUIs do not reach thermal equilibrium with core SW before exiting heliosphere

Motivation — why PUIs?

- Voyager **2** measurements show supersonic SW downstream of TS – streaming kinetic energy should become thermal energy but **~80%** of energy is unaccounted for

- V**2** can measure low-energy SW, high-energy cosmic rays, but not PUIs

- Inference: most of the downstream energy is contained in PUIs (Richardson **2008**)
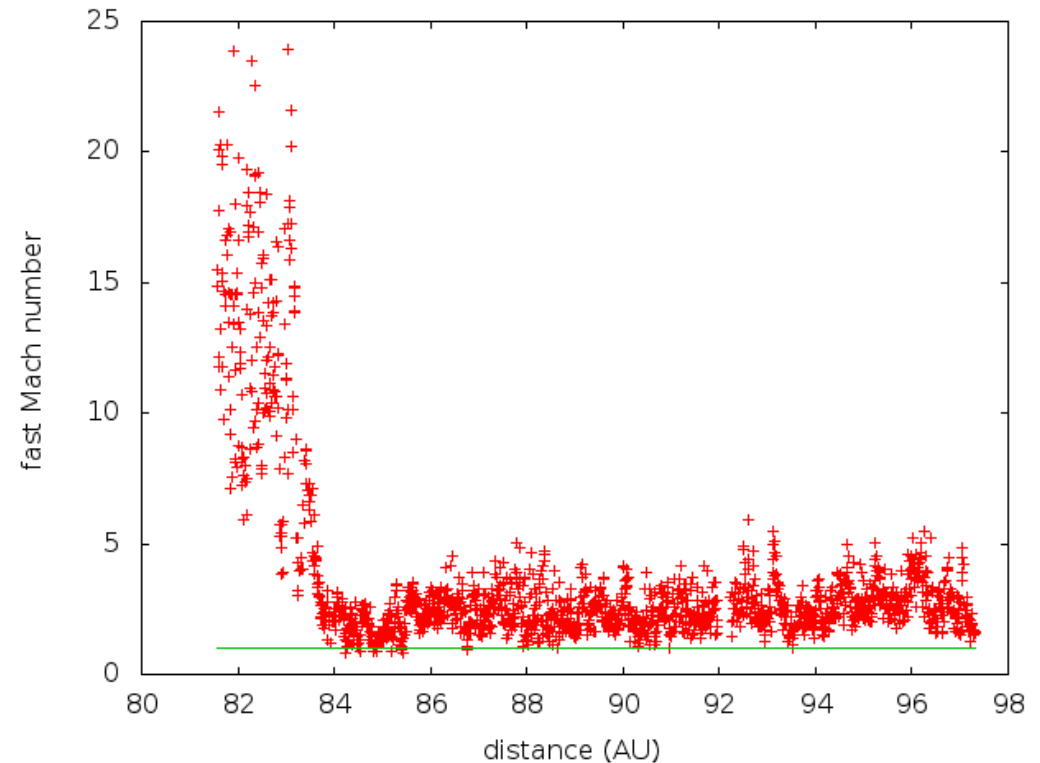
Fast-mode Mach number from Voyager **2** daily averaged data, 2007-2015. The green line shows M=**1**.

Pickup ions

- PUIs are much hotter, not in equilibrium with core SW - single normal distribution does not make sense

- Can model SW with Kappa distribution to get high-energy tails, but at the cost of fixed ratio of thermal to pickup ions

- Solution: two normal distributions
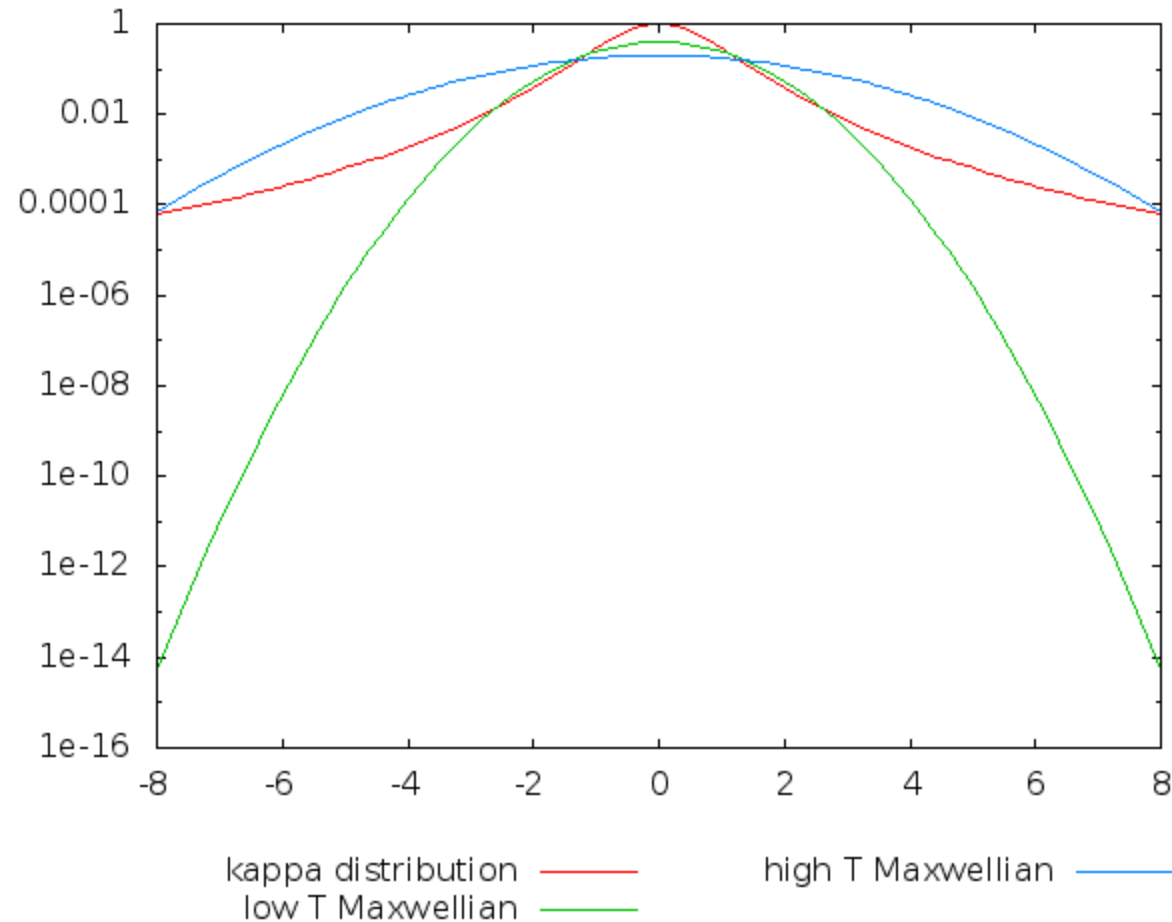
Physical model

- Multi-fluid magnetohydrodynamic (MHD) model

- One fluid for plasma mixture (thermal and pickup protons), three neutral fluids

- Since PUIs co-move with SW plasma, no need for separate equations for momentum and magnetic field – density and pressure sufficient

- Control fraction of plasma that is nonthermal with boundary conditions at TS

- Source terms for charge exchange, depending on both region and parent particles – can control which chemical reactions result in PUIs

Plasma mixture:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 = D_\Sigma,$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot \left(\rho \mathbf{u}\mathbf{u} + p^*\mathbf{I} - \frac{1}{4\pi}\mathbf{B}\mathbf{B} \right) = \sum_a (-\mathbf{H}^m_{pa} + \mathbf{H}^m_{ap} - \mathbf{H}^m_{Ia} + \mathbf{H}^m_{aI}) = \mathbf{M}_\Sigma,$$

$$\frac{\partial E}{\partial t} + \nabla \cdot \left((E + p^*)\mathbf{u} - \frac{1}{4\pi}(\mathbf{B} \cdot \mathbf{u})\mathbf{B} \right) = \sum_a (-H^e_{pa} + H^e_{ap} - H^e_{Ia} + H^e_{aI}) = E_\Sigma,$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{B} - \mathbf{B}\mathbf{u}) = 0.$$

Neutrals:

$$\frac{\partial \rho_a}{\partial t} + \nabla \cdot (\rho_a \mathbf{u}_a) = -H^\rho_{ap} - H^\rho_{aI} = D_a,$$

$$\frac{\partial \rho_a \mathbf{u}_a}{\partial t} + \nabla \cdot (\rho_a \mathbf{u}_a \mathbf{u}_a + p_a\mathbf{I}) = -\mathbf{H}^m_{ap} - H^m_{aI} = \mathbf{M}_a,$$

$$\frac{\partial e_a}{\partial t} + \nabla \cdot ((e_a + p_a)\mathbf{u}_a) = -H^e_{ap} - H^e_{aI} = E_a.$$

Pickup ions:

$$\frac{\partial \rho_I}{\partial t} + \nabla \cdot (\rho_I \mathbf{u}) = H^\rho_{Hp} = D_I,$$

$$\frac{\partial p_I}{\partial t} + \gamma\nabla \cdot (p_I \mathbf{u}) - (\gamma - 1)\mathbf{u} \cdot \nabla p_I = H^p_{Hp} - H^p_{IH} + H^p_{HI} = P_I$$
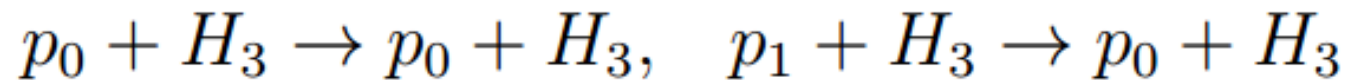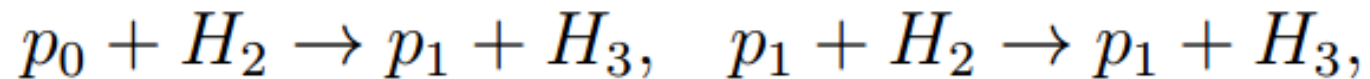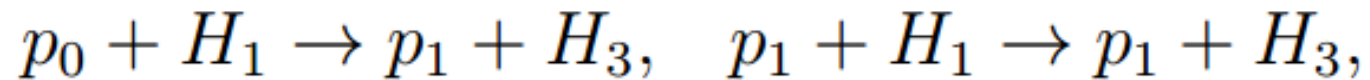
Source terms

- Products of a given charge exchange event depend not only on the parent particles but also the region - each set of products has distinct temperature, density profiles

- At least a dozen distinguishable populations possible – too unwieldy for multi-fluid model

- Solution: group all "hot" and "cold" plasma products with like products from other events, group all neutrals together which are born in the same region

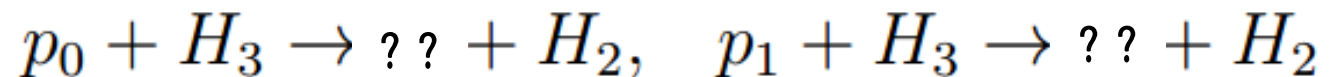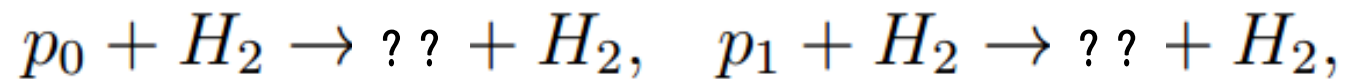- Separation justified by results of kinetic simulations (Malama et al. 2005)
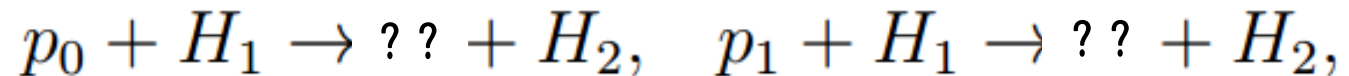
The first test

- In the LISM, allow PUIs to convect without charge exchange

$$p_0 + H_1 \rightarrow p_0 + H_1,$$
$$p_0 + H_2 \rightarrow p_0 + H_1,$$
$$p_0 + H_3 \rightarrow p_0 + H_1$$
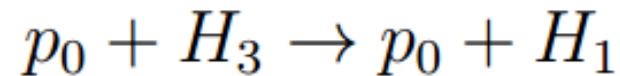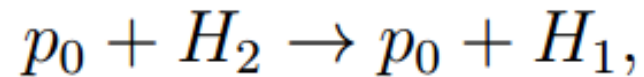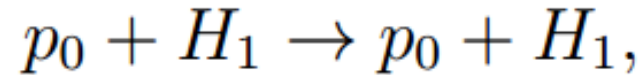
- In the super-sonic SW, use the reactions at right

$$p_0 + H_1 \rightarrow p_1 + H_3, \quad p_1 + H_1 \rightarrow p_1 + H_3,$$
$$p_0 + H_2 \rightarrow p_1 + H_3, \quad p_1 + H_2 \rightarrow p_1 + H_3,$$
$$p_0 + H_3 \rightarrow p_0 + H_3, \quad p_1 + H_3 \rightarrow p_0 + H_3$$

- In the helio-sheath, try two possibilities: all reactions result in PUIs, or none

$$p_0 + H_1 \rightarrow ?? + H_2, \quad p_1 + H_1 \rightarrow ?? + H_2,$$
$$p_0 + H_2 \rightarrow ?? + H_2, \quad p_1 + H_2 \rightarrow ?? + H_2,$$
$$p_0 + H_3 \rightarrow ?? + H_2, \quad p_1 + H_3 \rightarrow ?? + H_2$$

The second test

- The model does not solve a complete set of MHD equations for PUIs, just pressure and density

- To couple these relations to the mixture equations, an additional boundary condition is needed – apply at the termination shock

- Suitable conditions should depend only on mixture quantities and upstream PUI values – since the mixture equations are solved self-consistently, relations may depend on mixture values downstream

Shock boundary conditions

- First method – enforce entropy conservation for the thermal component, assuming the same compression ratio: $\frac{p}{\rho^\gamma}_{SW,1} = \frac{p}{\rho^\gamma}_{SW,2}$

- This assigns $p_{PUI,2} = p_{mix,2} - s^\gamma(p_{mix,1} - p_{PUI,1})$

- Second method – use Liouville theorem across the shock, assuming strong pitch-angle scattering (Fahr & Chalov **2008**):

$$f_{PUI,2}(v) = s\left(\frac{B_2}{B_1}\right)^{-\frac{3}{2}} f_{PUI,1}\left(v\left(\frac{B_2}{B_1}\right)^{-\frac{1}{2}}\right)$$

- Then $\rho_{PUI,2} = s\rho_{PUI,1}, \quad p_{PUI,2} = s\left(\frac{B_2}{B_1}\right)p_{PUI,1}$

- Third method: integrate kinetic transport equation across shock: $f_{PUI,2}(v) = f_{PUI,1}(s^{-\frac{1}{3}}v)$

- Then $\rho_{PUI,2} = s\rho_{PUI,1}, \quad p_{PUI,2} = s^{\frac{5}{3}}p_{PUI,1}$

Computation

- System solved on `256x96x128` spherical grid, `12-1200` AU exponential R spacing

- Grid, parallelization handled by Chombo

- Typical run: `512-1024` MPI tasks with `2` OpenMP threads found to be optimal for this problem

- Many runs to explore parameter space instead of fewer at higher resolution
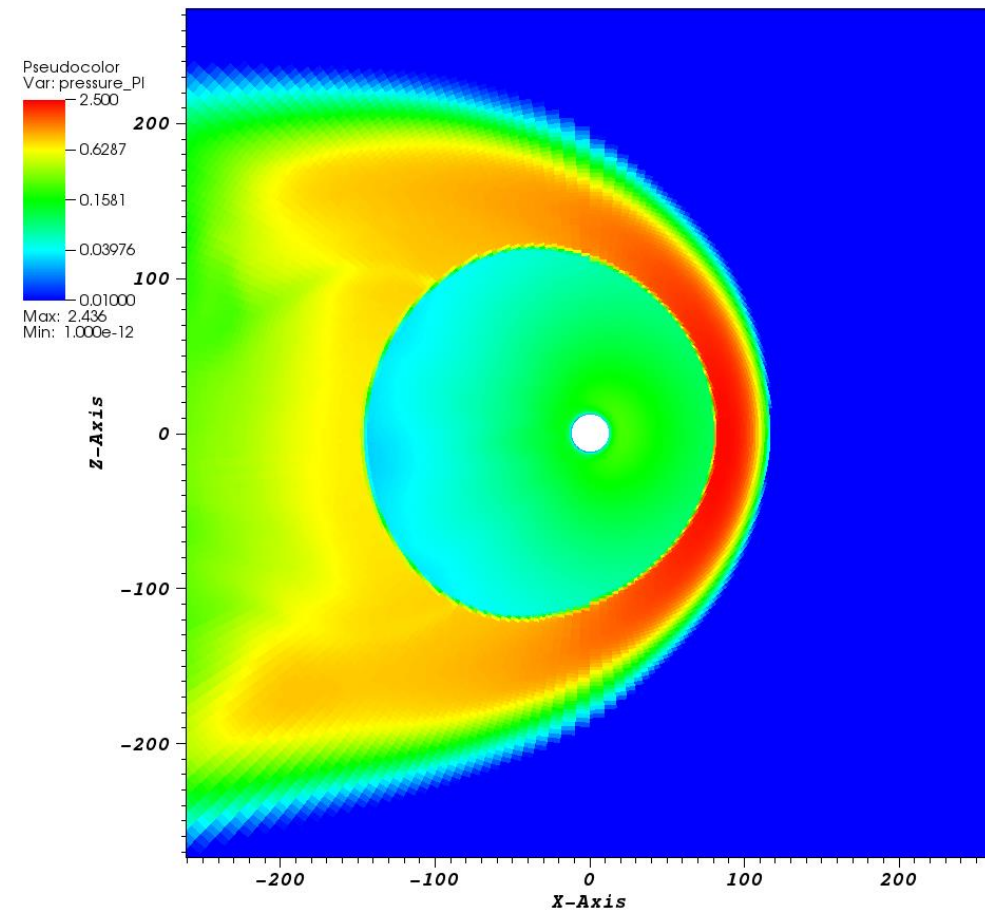
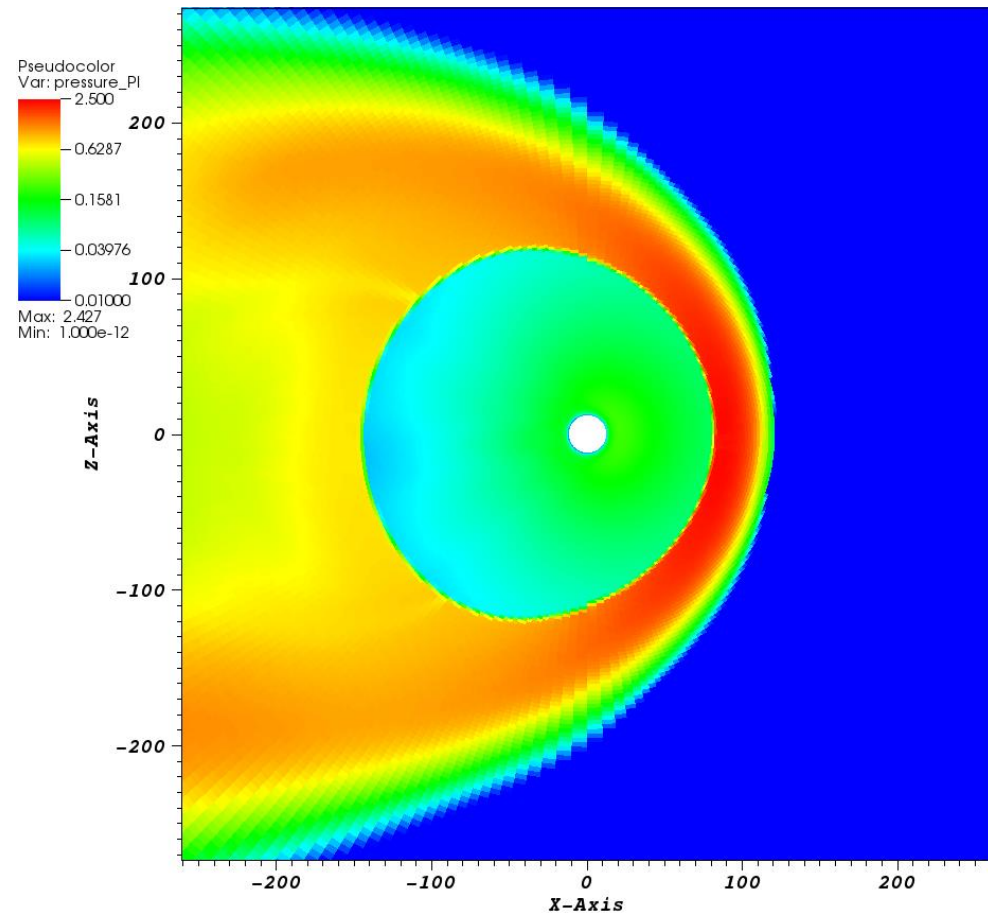- Used entire `50`k node-hour allocation
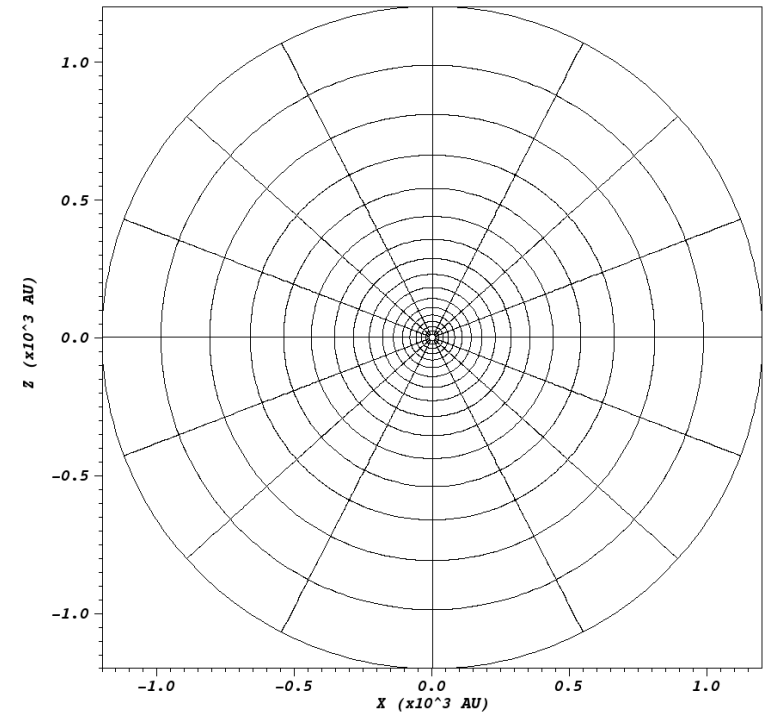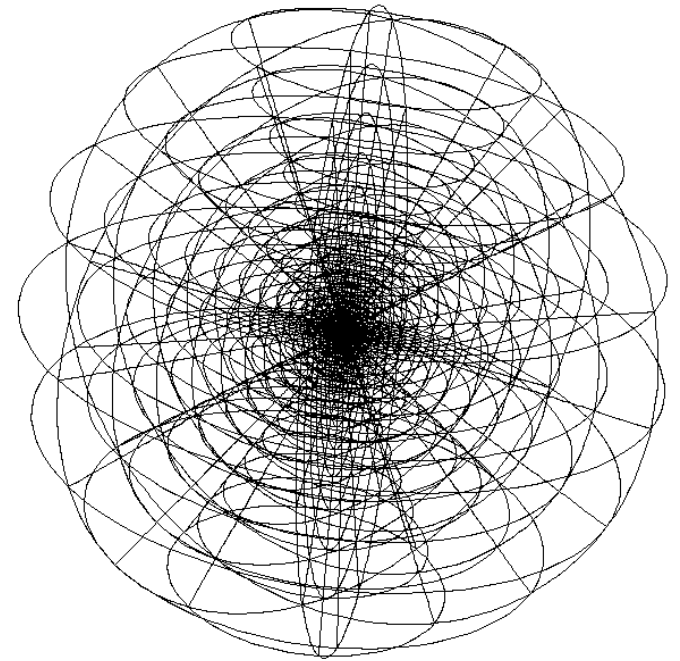
# Results
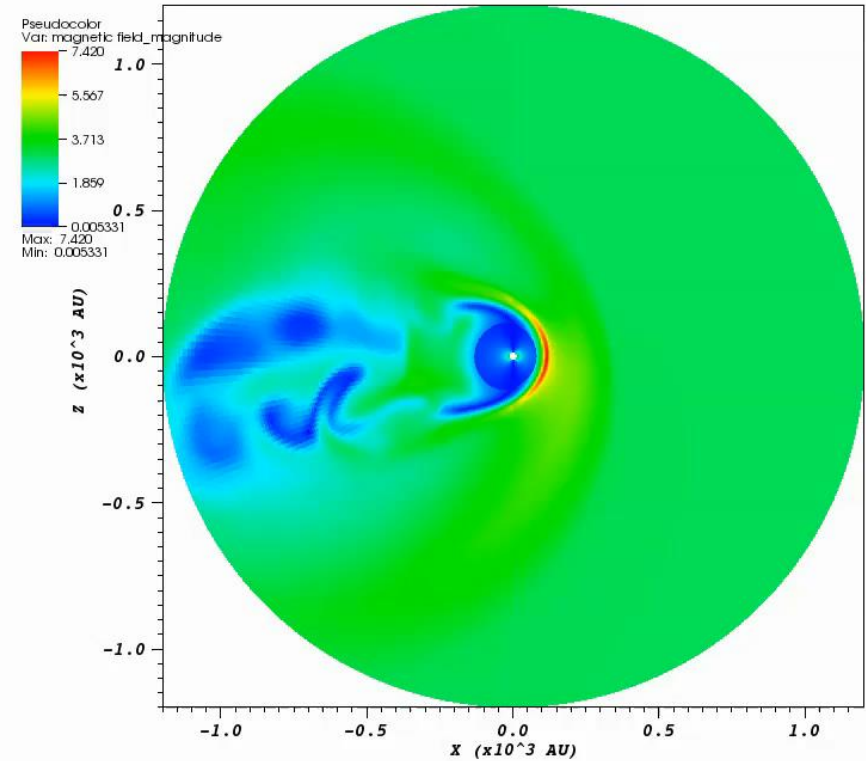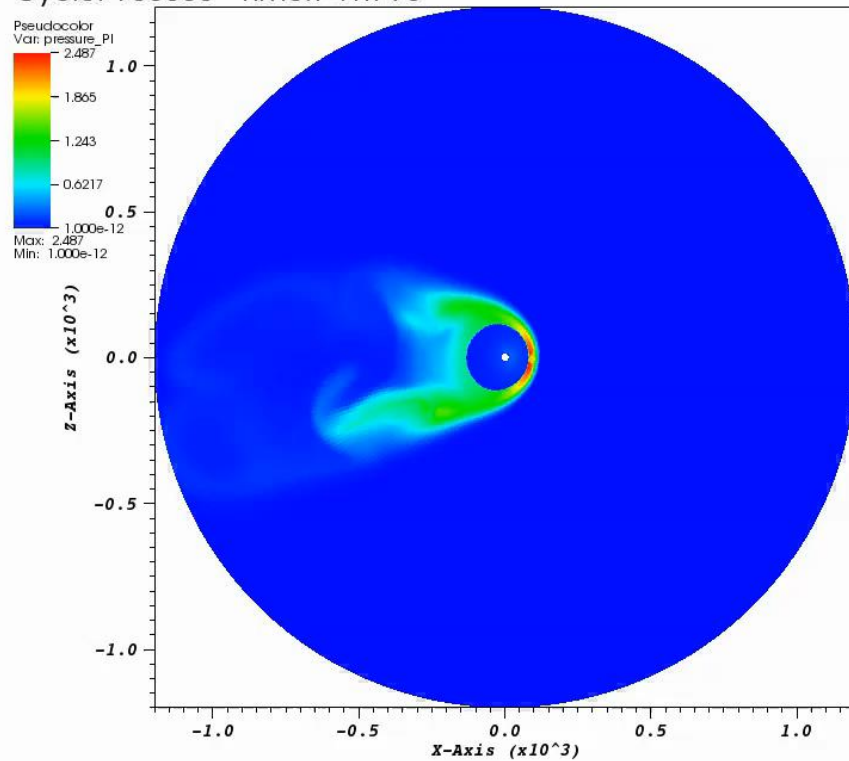
Effects of source terms

The heliopause expands as expected in the case (left)
that charge exchange in the heliosheath results in only
PUIs vs. only thermal protons, but the difference is
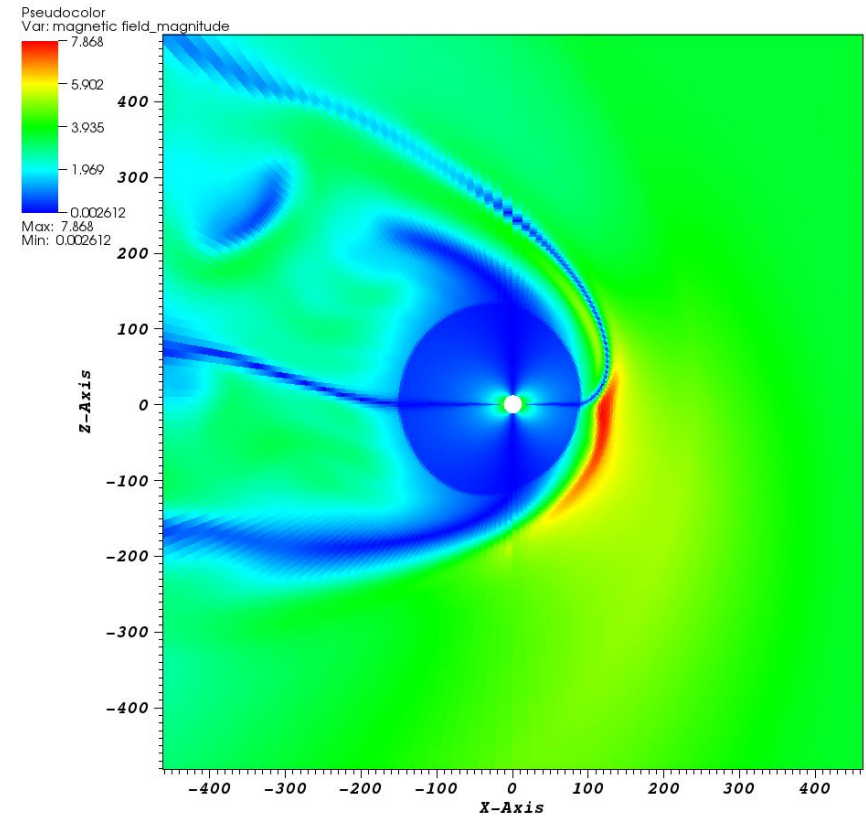minimal in the nose.

Effects of BCs

- PUIs with proper BCs necessary to reproduce

- Without PUIs, fast Mach number too low both upstream and downstream

- Source terms have less effect than anticipated in the V2 direction
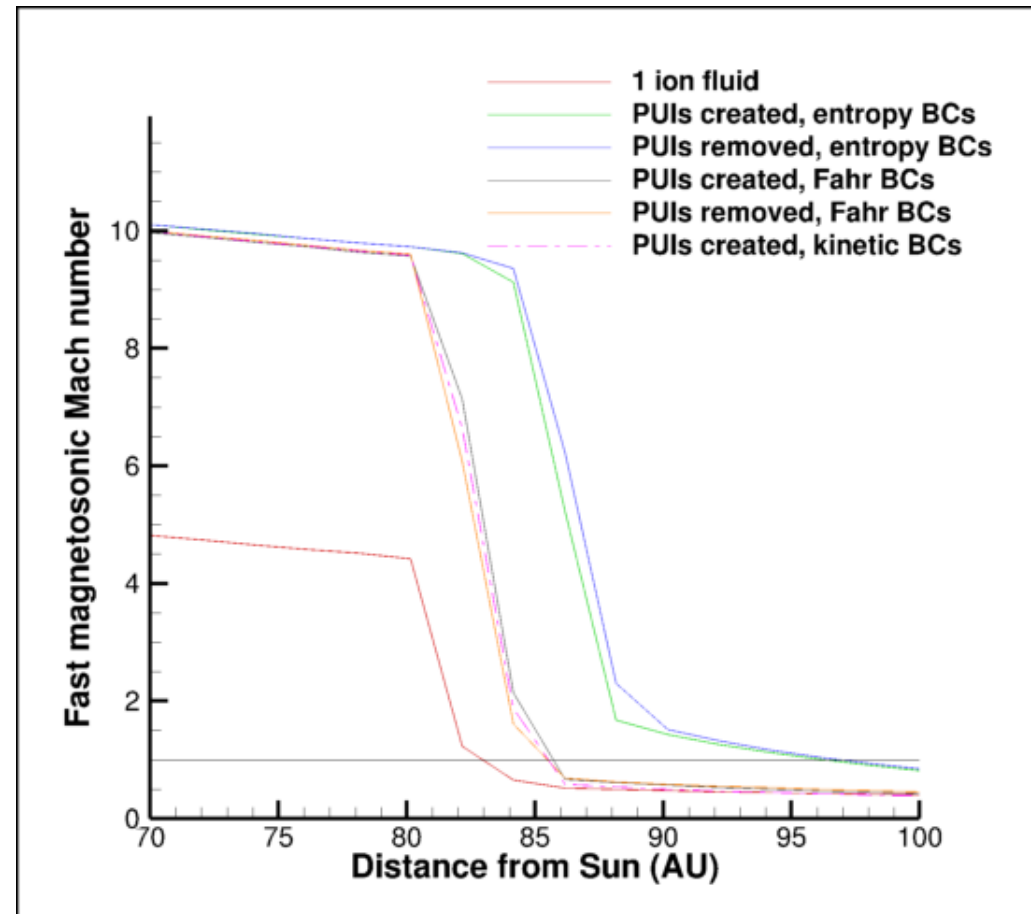
Effects of current sheet
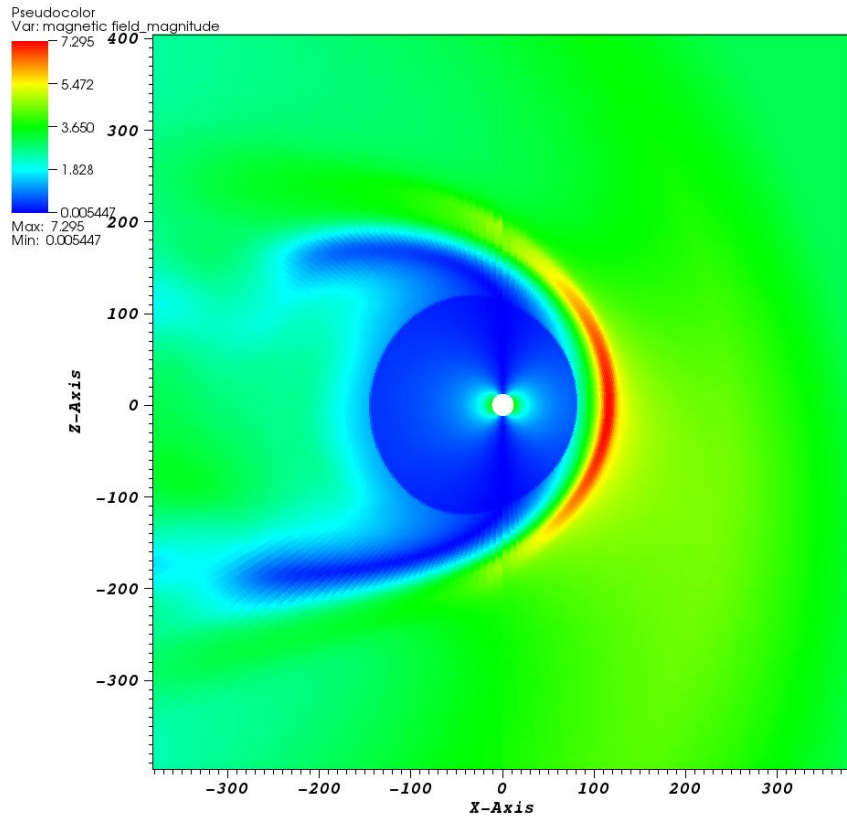
Heliospheric current sheet causes unrealistic artifacts.
Proper treatment requires time-dependent solar cycle.

References

- Fahr, H. J. & Chalov, S. V., Supersonic solar wind ion flows downstream of the termination shock explained by a two-fluid shock model, A&A **490**, L35–L38 (2008)

- Malama, Y. G., Izmodenov, V. V., & Chalov, S. V., Modeling of the heliospheric interface: multi-component nature of the heliospheric plasma, A&A **445**, 693–701 (2006)

- Richardson, J. D., Kasper, J. C., Wang, C., Belcher, J. W., & Lazarus, A. J., Cool heliosheath plasma and deceleration of the upstream solar wind at the termination shock, Nature, Volume **454**, Issue **7200**, pp. 63-66 (2008)